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RESEARCH MEMORANDUM

TURBINE DESIGN CONSIDERATIONS FOR TURBINE-PROPELLER ENGINE OPERATING OVER A RANGE OF FLIGHT CONDITIONS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The operation of a turbine-propeller engine over a range of flight conditions can impose a wide range of operating conditions on the turbine component. If efficient turbine operation is to be attained over this range of flight conditions, it is imperative that in the turbine design the entire range of required turbine operating conditions should be considered.

In the investigation reported herein, the compressor performance for one compressor typical of those employed in current turbine-propeller engines was used to determine the turbine design requirements for a turbine-propeller engine to be operated up to altitudes of 40,000 feet and flight velocities up to 600 miles per hour. The two modes of engine operation considered were (1) constant exhaust-nozzle area and (2) variable exhaust-nozzle area.

It was concluded that either mode of engine operation would result in efficient engine operation and that satisfactory turbine designs were obtainable for either mode of engine operation. Constant-exhaust-nozzle-area operation resulted in more severe turbine design requirements than variable-exhaust-nozzle-area operation. However, depending upon the flight conditions considered, the variations in exhaust-nozzle area required for efficient engine operation may be quite large.

INTRODUCTION

Operation of a turbine-propeller engine over a range of flight conditions can impose a wide range of operating conditions on the turbine component. The purpose of the investigation reported herein is to determine the turbine-exit annular area and pressure-ratio requirements for efficient engine operation with either constant engine geometry (constant exhaust-nozzle area) or variable engine geometry (variable exhaust-nozzle area). The compromises required between turbine requirements and engine performance dictated by practical turbine and engine considerations are considered in the investigation.

Under normal flight and engine operating conditions, the range of turbine operation encountered by a conventional turbine can usually be defined by the maximum range of pressure ratio over which the turbine must operate, because the variations in turbine equivalent rotative speed are usually small. In the analysis, therefore, only those flight conditions that impose the maximum variation in turbine pressure ratio need be considered.

Increasing altitude and flight-speed result in an increase in the over-all expansion ratio (turbine-inlet total pressure to ambient air pressure) for conventional turbine-propeller engines. Any portion, 2849
within limits, of the over-all expansion ratio may be imposed across the turbine. For a given over-all expansion ratio, the minimum pressure ratio across the turbine occurs for zero propeller thrust while the maximum pressure ratio occurs for zero jet thrust (maximum propeller thrust). The optimum split of pressure ratio between the turbine and the exhaust nozzle for a turbine-propeller engine at any operating condition (constant flight speed, altitude, rotative speed, and turbine-inlet temperature) is determined when a minimum specific fuel consumption or maximum thrust is obtained.

The maximum useful pressure ratio across a turbine occurs at the limiting-loading condition described in reference 1. In reference 2 it is shown that the condition of limiting loading determined the minimum permissible turbine-exit annular area required. The maximum pressure ratio at which the turbine is to be operated can therefore be used to determine the size of the required turbine-exit annular area. Selection of a turbine-exit annular area on this basis and a mode of engine operation then permit a determination of the range of pressure ratio over which the turbine must operate or the variations in exhaust-nozzle area required for efficient engine operation.

Typical turbine-propeller-engine characteristics for one engine were analytically investigated at the NACA Lewis laboratory to determine the turbine design requirements for such an engine under several flight conditions. The compressor performance data used in the analysis are typical for the type of compressor currently used in turbine-propeller engines. At design-point operation the pressure ratio is 7.32, the equivalent weight flow per unit frontal area is 26.9 pounds per square foot, and the compressor is operating near peak efficiency at 83 percent.

In the analysis, flight velocities varied from 0 to 600 miles per hour at sea level and from 400 to 600 miles per hour at an altitude of 40,000 feet. Engine operating conditions of design rotative speed and turbine-inlet temperature (2060° R) were also specified. Two modes of engine operation were considered: (1) constant exhaust-nozzle area and (2) variable exhaust-nozzle area or constant turbine total-pressure ratio.

The turbine design requirements investigated were turbine-exit annular area and turbine total-pressure ratio. In addition, the exhaust-nozzle-area requirements and the variations in engine efficiency with exhaust-nozzle area are presented.

SYMBOLS

The following symbols are used in this report:

A_a	annular aréa, sq ft
A_c	compressor frontal area, sq ft
F	jet thrust, lb
n	polytropic exponent
P	power, hp
p	pressure, lb/sq ft
T	temperature, $^{\circ}$R
V	velocity, ft/sec
w	weight flow, lb/sec
δ	ratio of pressure to 2116 pounds per square foot
η	efficiency
θ	ratio of temperature to 518.4° R
ρ	gas density, lb/cu ft

Subscripts:

c	compressor
g	gear box
n	net
p	propeller
s	sea-level static

t turbine

x axial component of velocity

1 ambient air

2 compressor inlet

3 compressor exit 2849

4 turbine inlet

5 turbine exit

6 exhaust-nozzle exit

Superscripts:

' total, or stagnation, state

* shaft horsepower plus equivalent shaft horsepower of net jet thrust

ANALYSIS

Assigned Conditions

As stated in the INTRODUCTION, only those flight conditions that impose the maximum variation in turbine pressure ratio need be considered, because under normal flight and engine operating conditions the variations in turbine equivalent rotative speed are usually small.

The maximum over-all expansion ratio and, for conventional turbine-propeller engines, the maximum turbine pressure ratio will occur when the following conditions are concurrently achieved by the engine: highest flight speed, turbine-inlet temperature, rotative speed, and lowest ambient air temperature. The minimum over-all expansion ratio (and turbine pressure ratio) will occur at the take-off condition for engines having conventional compressor performance because there is no ram pressure ratio. A turbine should, therefore, be designed to operate satisfactorily at the following two conditions: (1) take-off and (2) maximum altitude, flight velocity, turbine-inlet temperature, and rotative speed. The turbine design requirements were therefore determined for the following conditions:

Altitude, ft	0	40,000
Percent design rotative speed	100	100

Turbine-inlet total temperature, °R	2060	2060
Flight velocity, mph	0	600

Additional flight velocities at the two altitudes were also considered.

Assumed Conditions

2849 The following conditions were assumed for the analysis:

Ram efficiency, percent	100
Propeller efficiency, η_p, percent	80
Gear-box efficiency, η_g, percent	95
Burner total-pressure ratio, p_4'/p_3'	0.95
Turbine internal efficiency, percent	85
Tail-cone total-pressure ratio, p_6'/p_5'	0.95
Ratio of specific heats in compressor	1.40
Ratio of specific heats in turbine	1.33
Gas constant, ft-lb/(lb)(°R)	53.4

The turbine equivalent weight flow $w_4 \sqrt{\theta_4'}/\delta_4'$ was assumed to be constant; this implies that the turbine stator is choked for all conditions analyzed. The air flow through the compressor was assumed equal to the gas flow through the turbine. The jet velocity was calculated from the ratio of exhaust-nozzle total pressure to ambient air pressure p_6'/p_1, a nozzle efficiency of 100 percent, and temperature T_6'.

Cycle Analysis

Compressor performance. - With the use of the over-all compressor characteristics shown in figure 1, a cycle analysis was made of equilibrium engine operation.

The continuity requirements between the turbine and compressor may be expressed in the same manner (eq. (1)) as in reference 2. In terms of the nomenclature used herein, equation (1) of reference 2 becomes

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$$\frac{w_2\sqrt{\theta_2'}}{\delta_2'} = \frac{p_3'}{p_2'}\sqrt{\frac{T_2'}{T_4'}}\left(\frac{w_4\sqrt{\theta_4'}}{\delta_4'} \times \frac{p_4'}{p_3'}\right) \tag{1}$$

where, as in reference 2, it is assumed that $w_4\sqrt{\theta_4'}/\delta_4'$ and p_4'/p_3' are constant. Assuming $w_4\sqrt{\theta_4'}/\delta_4'$ is constant implies that the turbine stator is choked for all the operating conditions considered. Thus constant-temperature-ratio lines of turbine-inlet to compressor-inlet temperature T_4'/T_2' are straight and would pass through the origin. The 2849
slopes of these temperature-ratio lines are dependent upon the selection of a turbine-inlet temperature at some compressor operating condition.

The compressor performance map of figure 1 with lines of constant temperature ratio superimposed upon it is shown in figure 2. The temperature-ratio lines shown in figure 2 were constructed for an assigned turbine-inlet temperature of 2060° R at sea-level static and compressor design-point operation. It is thus possible to determine from figure 2 the compressor operating point for an assigned combination of the following: turbine-inlet total temperature, rotative speed, flight speed, and altitude. The four points (A, B, C, and D) on this map represent the compressor operating condition for the assigned altitude and flight conditions at constant turbine-inlet temperature (2060° R) and rotative speed (100 percent of rated rotative speed).

Exhaust-nozzle area. - For any flight condition in which the pressure ratio across the exhaust nozzle was equal to, or greater than, that required for choking, the choking exhaust-nozzle area was used. When the pressure ratio was not great enough to choke the exhaust nozzle, ambient air pressure was assumed at the exit of the exhaust nozzle in order to calculate the exhaust-nozzle area.

Engine power. - In order to determine the variations in net engine power output at a given flight condition for varying amounts of the over-all expansion ratio taken across the turbine, the net jet thrust was converted into an equivalent shaft horsepower by using the assumed propeller efficiency of 80 percent. That is,

$$P^* = \eta_g(P_t - P_c) + \frac{F_n V_1}{550\eta_p} \tag{2}$$

Because the jet thrust cannot be converted into an equivalent shaft horsepower in the above mentioned manner at the static sea-level condition, a conversion factor between shaft horsepower and static thrust must be assumed. For this analysis the conversion factor was assumed to be 3.62, and thus for sea-level static conditions

$$P^{*} = \eta_g(P_t - P_c) + \frac{F_s}{3.62} \tag{3}$$

Turbine Performance

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In order for the turbine to operate satisfactorily, it must be capable of utilizing the maximum pressure ratio imposed across it. The maximum useful pressure ratio across a turbine occurs at the limiting-loading condition and is determined by the turbine geometry. The concept of turbine limiting loading is discussed in detail in reference 2, in which it is shown that, over a wide range of rotor-exit blade angles, the limiting work output of a turbine is reached at a definite exit axial Mach number. The exit axial Mach number at which the turbine reaches limiting loading is a function of the trailing-edge blockage of the last rotor blade. For purposes of this analysis, limiting loading was assumed to occur at an exit axial Mach number of 0.68. It is possible to calculate the maximum useful pressure ratio from the turbine geometry in the following manner:

Writing the continuity equation at the turbine exit

$$w = \rho_5 V_{x,5} A_{a,5} \tag{4}$$

and assuming the pressure ratio and temperature ratio across the turbine to be related by some polytropic exponent n (determined by the small-stage efficiency assumed) permit equation (4) to be written as follows:

$$\frac{p_4'}{p_5'} = \left(\frac{\rho_5 V_{x,5}\sqrt{T_5'}/p_5'}{w\sqrt{T_4'}/p_4'}\right)^{\frac{2n}{n+1}} (A_{a,5})^{\frac{2n}{n+1}} \tag{5}$$

The weight-flow term $w\sqrt{T_4'}/p_4'$ will be constant because the first stator was assumed to choke. For zero tangential component of velocity at the turbine exit, the specific mass-flow term $\frac{\rho_5 V_{x,5}\sqrt{T_5'}}{p_5'}$ will be constant because limiting loading is assumed to occur in this analysis at a constant exit axial Mach number of 0.68. This analysis may also be assumed to apply to those conditions for which some exit whirl exists because the specific mass-flow term $\frac{\rho_5 V_{x,5}\sqrt{T_5'}}{p_5'}$ is insensitive to exit tangential components of velocity near zero. The value of the constant formed by the ratio of $w\sqrt{T_4'}/p_4'$ and $\dfrac{\rho_5 V_{x,5}\sqrt{T_5'}}{p_5'}$ is determined by the selection of the turbine-inlet temperature and compressor operating point that fixed the slopes of the temperature-ratio lines in figure 2. From equation (5), then, it is possible to determine the maximum useful total-pressure ratio across the turbine from the exit annular area and the polytropic exponent n. 2849

The value of the polytropic exponent (1.25) used in this analysis corresponds to a turbine internal efficiency of 85 percent at a total-pressure ratio of 7. This means of specifying turbine efficiency is not in agreement with the assumption of constant turbine internal efficiency used throughout the rest of the analysis; however, over the range of turbine pressure ratios covered in the analysis, the resulting error is negligible.

RESULTS AND DISCUSSION

The results of this analysis are presented in figures 3 to 6. The turbine design requirements can be determined from these figures once the mode of engine operation and range of engine operating conditions have been assigned. In table I are presented the turbine design requirements for constant-exhaust-nozzle-area and variable-exhaust-nozzle-area (constant turbine pressure ratio) modes of engine operation over the same range of flight conditions.

Results of Analysis

Figure 3. - The effect of altitude and flight speed on the over-all expansion ratio (turbine-inlet total pressure to ambient air pressure) for design rotative speed and design turbine-inlet temperature is presented in figure 3. It is immediately apparent from this figure that the turbine and exhaust nozzle must be capable of utilizing a much greater pressure ratio at the altitude flight conditions than at sea-level static conditions.

Figure 4. - In figure 4(a) is presented the sea-level variation in net engine power output with exhaust-nozzle area for lines of constant flight speed and turbine total-pressure ratio for design engine rotative speed and design turbine-inlet temperature. The solid lines represent constant flight velocity and the dashed lines represent constant turbine total-pressure ratio. Figure 4(b) is a similar plot for an altitude of 40,000 feet. This figure results from the cycle analysis and is very useful in determining the most efficient modes of engine operation.

Figure 5. - The effect of exhaust-nozzle area on jet velocity for design rotative speed and design turbine-inlet temperature at the

sea-level static condition is presented in figure 5. The take-off jet velocity is a critical factor in the design of turbine-propeller engines, and this figure is useful in rapidly determining its magnitude.

Figure 6. - From figure 6 the maximum useful turbine total-pressure ratio obtainable for a given exit annular area can be determined. This figure was constructed on the assumption that the first stator blade row chokes and that the turbine reaches limiting loading at an exit axial Mach number of 0.68. Except for the selection of the turbine-inlet temperature and the compressor operating point, which determine the first turbine stator throat area, figure 6 is independent of turbine-inlet conditions and rotative speed. In this figure the maximum useful turbine total-pressure ratio obtainable is plotted against the ratio of turbine-exit annular area to compressor frontal area (fig. 6(a)), the ratio of turbine-exit tip diameter to compressor tip diameter for turbines having an exit hub-tip radius ratio of 0.6 (fig. 6(b)), and the turbine-exit hub-tip radius ratio for turbines having a ratio of turbine-exit tip diameter to compressor tip diameter of 1.22 (fig. 6(c)), respectively.

Turbine Design Requirements

Turbine design requirements for two modes of engine operation at two flight conditions were selected from figures 4 to 6 and are listed in table I. The turbine design requirements shown are the extremes over which the turbine must be operated.

Variable exhaust-nozzle area. - For the variable-exhaust-nozzle-area case, the turbine was assumed to be at limiting loading for both the sea-level and the altitude condition. The maximum useful total-pressure ratio assigned was 6.0, which represents a good compromise between turbine requirements and engine performance over the range of flight conditions considered. In order to obtain a pressure ratio of 6.0 without exceeding limiting loading, the ratio of turbine-exit annular area to compressor frontal area must be 0.89 or larger (see fig. 6). It is seen from the tabular values obtained from figure 4 that in going from sea-level static conditions (ratio of exhaust-nozzle area to compressor frontal area of 1.40) to a flight velocity of 600 miles per hour at 40,000 feet (ratio of exhaust-nozzle area to compressor frontal area of 0.83) requires a reduction in exhaust-nozzle area of 41 percent for efficient engine operation. If the exhaust-nozzle area were not closed down at the altitude condition, inefficient engine operation would result because the turbine is designed to utilize a maximum pressure ratio of only 6.0. With the exhaust-nozzle area the same at altitude as at sea level, there would have to be a considerable loss in total pressure in the tail cone in order to satisfy continuity considerations. However, it is apparent from figure 4(b) that at the altitude condition the turbine could be designed for any maximum useful pressure ratio from 6 to 10 and efficient engine operation will be obtained. If the turbine is designed for a pressure ratio of 6.0, it is seen from figure 4(b) that efficient engine operation at altitude from flight velocities of 400 to 600 miles per hour is possible without varying the exhaust-nozzle area. At sea level, however, it is seen from figure 4(a) that, over the range of flight velocity considered, a large variation in exhaust-nozzle area would be required for efficient engine operation.

Constant exhaust-nozzle area. - For the constant-exhaust-nozzle-area case shown in the last two columns of table I, the turbine was assumed to be at limiting loading at only the altitude condition. At altitude, the turbine total-pressure ratio assigned was 9.0, for which figure 6 shows a required ratio of turbine-exit annular area to compressor frontal area of 1.28. Figure 4(b) shows that a ratio of exhaust-nozzle area to compressor frontal area of 1.27 is required for efficient engine operation at the altitude condition with this assigned maximum useful pressure ratio. At the sea-level static condition, it is seen from figure 4(a) that for an engine with this geometry the turbine will be operating with a pressure ratio of 5.9, well away from the limiting-loading condition. Figure 4(a) shows that for the sea-level static conditions the net engine power output of this engine geometry, while high, could be improved considerably if a larger exhaust-nozzle area could be used. However, the exhaust-nozzle area would have to be made unduly large in order to achieve much increase in engine output at this condition. It might also be noted from figure 4 that at altitude the net engine power output of the constant-exhaust-nozzle-area design is slightly higher at all flight velocities than for the variable-exhaust-nozzle-area design (more efficient engine operation), but at the take-off condition it is slightly less. The difference between the two modes of engine operation for other flight velocities at sea level is negligible (fig. 4(a)) up to 400 miles per hour. At the higher flight velocities, the constant-exhaust-nozzle-area mode is less efficient.

For the same hub-tip radius ratio of 0.6 at the turbine exit, table I (fig. 6(b)) shows that the ratio of turbine-exit tip diameter to compressor tip diameter for the variable-exhaust-nozzle-area case is 1.18, while for the constant-exhaust-nozzle-area case it increases to 1.41, a 20-percent increase in turbine tip diameter. The only other alternative to increasing the turbine tip diameter would be to decrease the hub-tip radius ratio at the turbine exit. From figure 6(c), it is seen that the hub-tip radius ratio for a fixed ratio of turbine tip diameter to compressor tip diameter of 1.22 would be 0.37 for the constant-area case and 0.63 for the variable-area case. A practical lower limit on hub-tip radius ratios for turbines is usually around 0.6 because the blade aerodynamics become a problem at the lower radius ratios. For these reasons the turbine tip diameter will, in all probability, be greater for the constant-exhaust-nozzle-area design than for the variable-exhaust-nozzle-area design.

The take-off jet velocity listed in table I (fig. 5) for either design is quite low. This indicates that the majority of the take-off thrust is derived from the propeller.

<u>General discussion</u>. - The manner in which a turbine-propeller engine is operated has a prominent effect on the turbine design requirements. If the engine is to have a constant exhaust-nozzle area for all flight conditions, the turbine must be capable of operating efficiently over a range of pressure ratio. The maximum pressure ratio across the turbine occurs at altitude, and the exhaust-nozzle area required at take-off for efficient engine operation determines the magnitude of the maximum pressure ratio. For instance, if an engine designed for a maximum pressure ratio at altitude less than the value of 9.0 selected in the last column of table I is considered, efficient operation at altitude with such a design requires the exhaust-nozzle area to be reduced from that required for a pressure ratio of 9.0. At sea-level static conditions, however, it is apparent from figure 4(a) that this reduced area would lower the engine efficiency since the net horsepower output of the engine for the same turbine-inlet conditions drops rapidly with decreasing exhaust-nozzle area.

The operating points for the compressor under several flight conditions at maximum turbine-inlet temperature (2060° R) and design rotative speed are shown on the compressor map in figure 2. Between take-off and a flight velocity of 600 miles per hour at 40,000 feet, the compressor internal efficiency drops from 83 to 78 percent. This drop in compressor efficiency occurs for either mode of engine operation discussed. The turbine efficiency was assumed constant for these two points of engine operation even though the turbine pressure ratio changes from 5.9 to 9.0 for constant-exhaust-nozzle-area operation. On the basis of existing knowledge of turbine performance, high efficiency with little variation over such a range of pressure ratio is feasible in a good turbine design.

It has been assumed for the purpose of the analysis given herein that the turbine will operate efficiently at limiting loading. Actual turbine performance indicates, however, a slight deterioration in turbine performance when limiting loading is approached and a marked deterioration in performance when limiting loading is exceeded. For these reasons it is good design practice to provide a certain margin of safety in the turbine design so that limiting loading is never encountered under any of the flight conditions contemplated. This may easily be done by using a slightly larger exit annular area for the turbine than indicated by the limiting-loading condition.

If the variable-exhaust-nozzle-area operation is employed as in table I, a large variation in exhaust-nozzle area is required for efficient engine operation at the flight conditions considered. This mode of engine operation simplifies the turbine design requirements in that it reduces the maximum pressure ratio at which the turbine operates and the range of pressure ratio (zero for the case considered) over which good turbine efficiency is required. However, a variable-exhaust-nozzle-area mode of engine operation makes the engine control problem more complex.

The turbine for constant-exhaust-nozzle-area design would not only have a turbine tip diameter greater than the variable-exhaust-nozzle-area turbine for the same hub-tip radius ratio at the turbine exit but, because of the increased maximum pressure ratio, would require more turbine stages. 2849

An important consideration for turbine-propeller engines is that the major part of take-off thrust should be obtained from the propeller because it is usually a more efficient thrust-producing mechanism at take-off than the exhaust nozzle. In this respect there is little difference between either mode of engine operation. Both have equally low jet velocities and about the same turbine total-pressure ratio at take-off.

It can be concluded, therefore, that constant-exhaust-nozzle-area operation results in more severe turbine design requirements than variable-exhaust-nozzle-area operation. However, satisfactory turbine designs can be achieved for either mode of engine operation.

SUMMARY OF RESULTS

The problem of selecting the turbine design requirements for a range of turbine-propeller engine operation was investigated by determining the turbine design requirements of a particular turbine-propeller engine operating at two altitudes and various flight speeds. Two modes of engine operation were considered: (1) variable exhaust-nozzle area and (2) constant exhaust-nozzle area.

The following results were obtained:

(1) Efficient engine operation over a range of flight conditions was obtained with either constant- or variable-exhaust-nozzle-area operation.

(2) Satisfactory turbine designs were obtained for either constant- or variable-exhaust-nozzle-area operation. However, a turbine for constant-exhaust-nozzle-area operation will, in general, be larger both in tip diameter and number of stages than a turbine for variable-exhaust-nozzle-area operation.

(3) By the use of a variable exhaust-nozzle area, the maximum pressure ratio at which the turbine operates and the range of pressure ratio over which the turbine operates were reduced. However, in order to

achieve a substantial reduction in the maximum pressure ratio at which the turbine operates and the range of pressure ratio over which the turbine operates, while maintaining efficient engine operation, may require a large variation in the exhaust-nozzle area.

(4) Both modes of engine operation had very good take-off characteristics in that the propeller delivered the majority of the take-off thrust (low jet velocity).

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CONCLUSION

The turbine design requirements for a turbine-propeller engine should be based on a consideration of the range of flight conditions over which the engine is to perform. Either constant- or variable-exhaust-nozzle-area operation will result in efficient engine performance, and satisfactory turbine designs are obtainable for either mode of engine operation. However, constant-exhaust-nozzle-area operation results in more severe turbine design requirements than variable-exhaust-nozzle-area operation.

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REFERENCES

1. Hauser, Cavour H., and Plohr, Henry W.: Two-Dimensional Cascade Investigation of the Maximum Exit Tangential Velocity Component and Other Flow Conditions at the Exit of Several Turbine-Blade Designs at Supercritical Pressure Ratios. NACA RM E51F12, 1951.

2. English, Robert E., Silvern, David H., and Davison, Elmer H.: Investigation of Turbines Suitable for Use in a Turbojet Engine with High Compressor Pressure Ratio and Low Compressor-Tip Speed. I - Turbine-Design Requirements for Several Engine Operating Conditions. NACA RM E52A16, 1952.

TABLE I. - TURBINE AND ENGINE DESIGN CONDITIONS FOR TWO MODES OF ENGINE OPERATION AT TWO FLIGHT CONDITIONS

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	Variable exhaust-nozzle area		Constant exhaust-nozzle area	
Altitude, ft	0	40,000	0	40,000
Flight velocity, mph	0	600	0	600
Turbine-inlet total temperature, ^{o}R	2060	2060	2060	2060
Turbine total-pressure ratio	6.0	6.0	5.9	9.0
Over-all expansion ratio	6.94	13.68	6.94	13.68
Ratio of exhaust-nozzle area to turbine-exit annular area	1.57	0.93	0.99	0.99
Ratio of turbine-exit annular area to compressor frontal area	0.89	0.89	1.28	1.28
Ratio of exhaust-nozzle area to compressor frontal area	1.40	0.83	1.27	1.27
Shaft horsepower per unit compressor frontal area (includes equivalent shp of jet thrust), hp	2290	1330	2240	1350
Jet velocity, ft/sec	680		750	
Ratio of turbine-exit tip diameter to compressor tip diameter (turbine-exit-hub-tip radius ratio, 0.6)	1.18	1.18	1.41	1.41

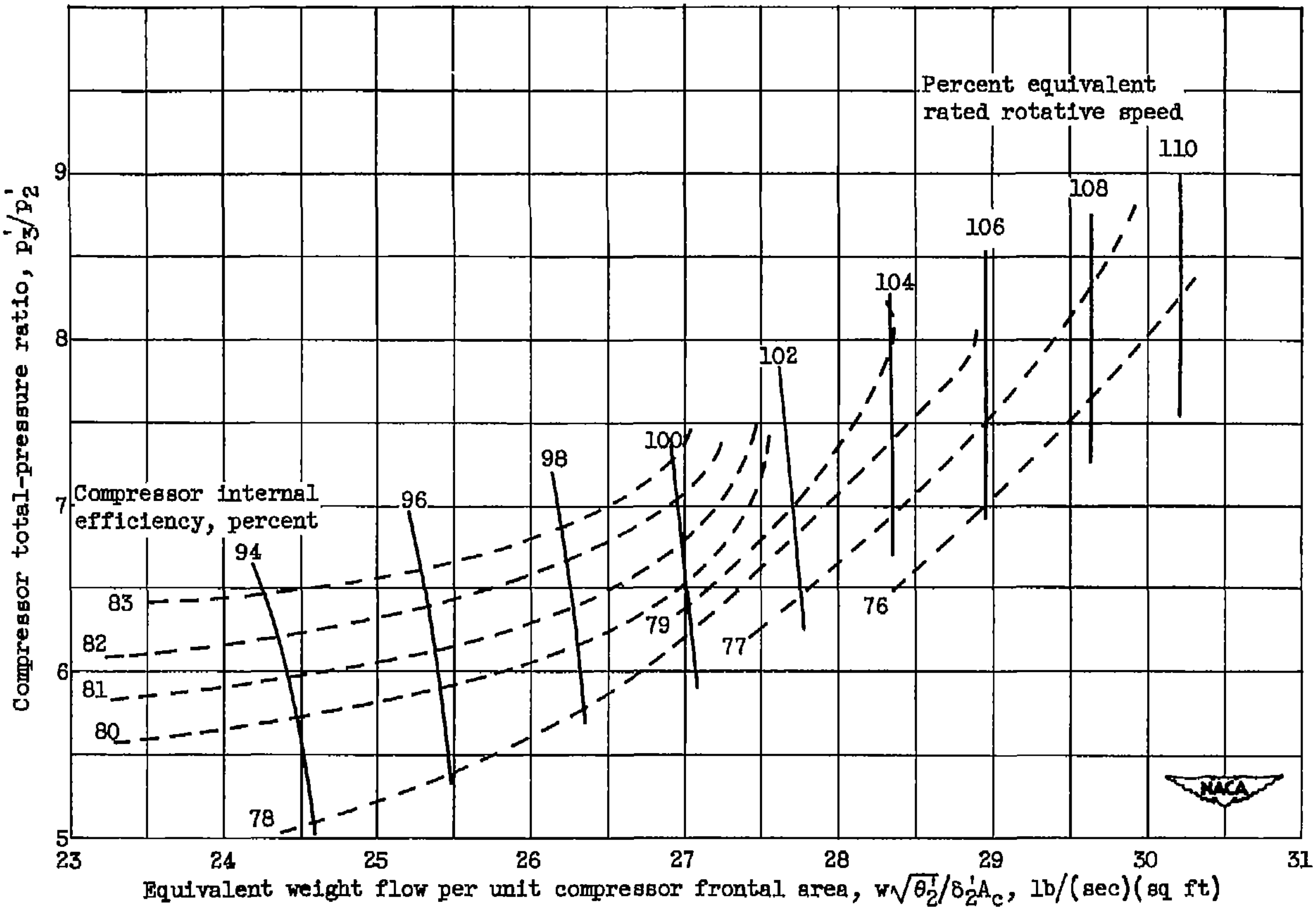


Figure 1. - Compressor performance map.

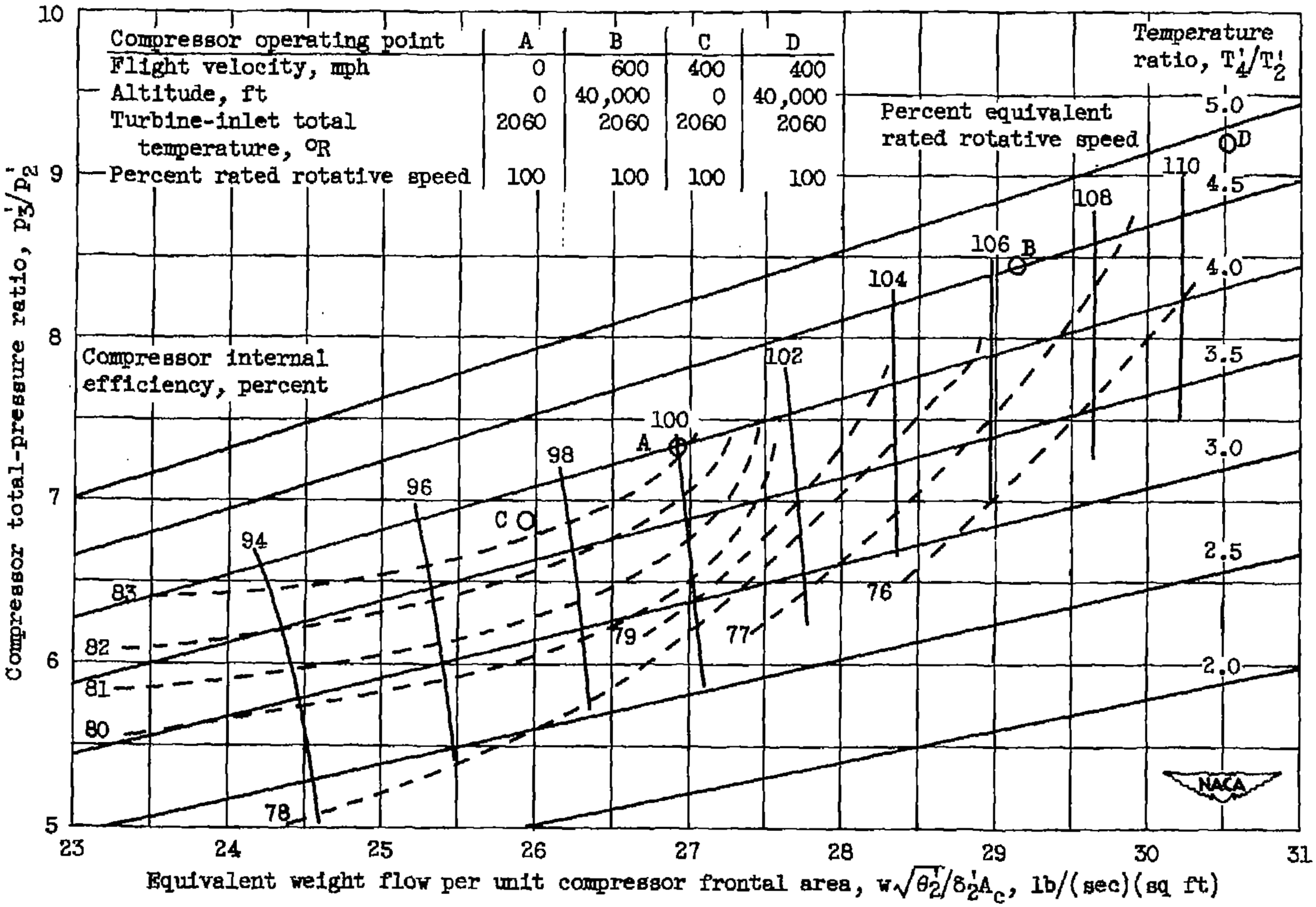


Figure 2. - Compressor performance map with superimposed temperature-ratio lines showing compressor operating conditions for several flight conditions.

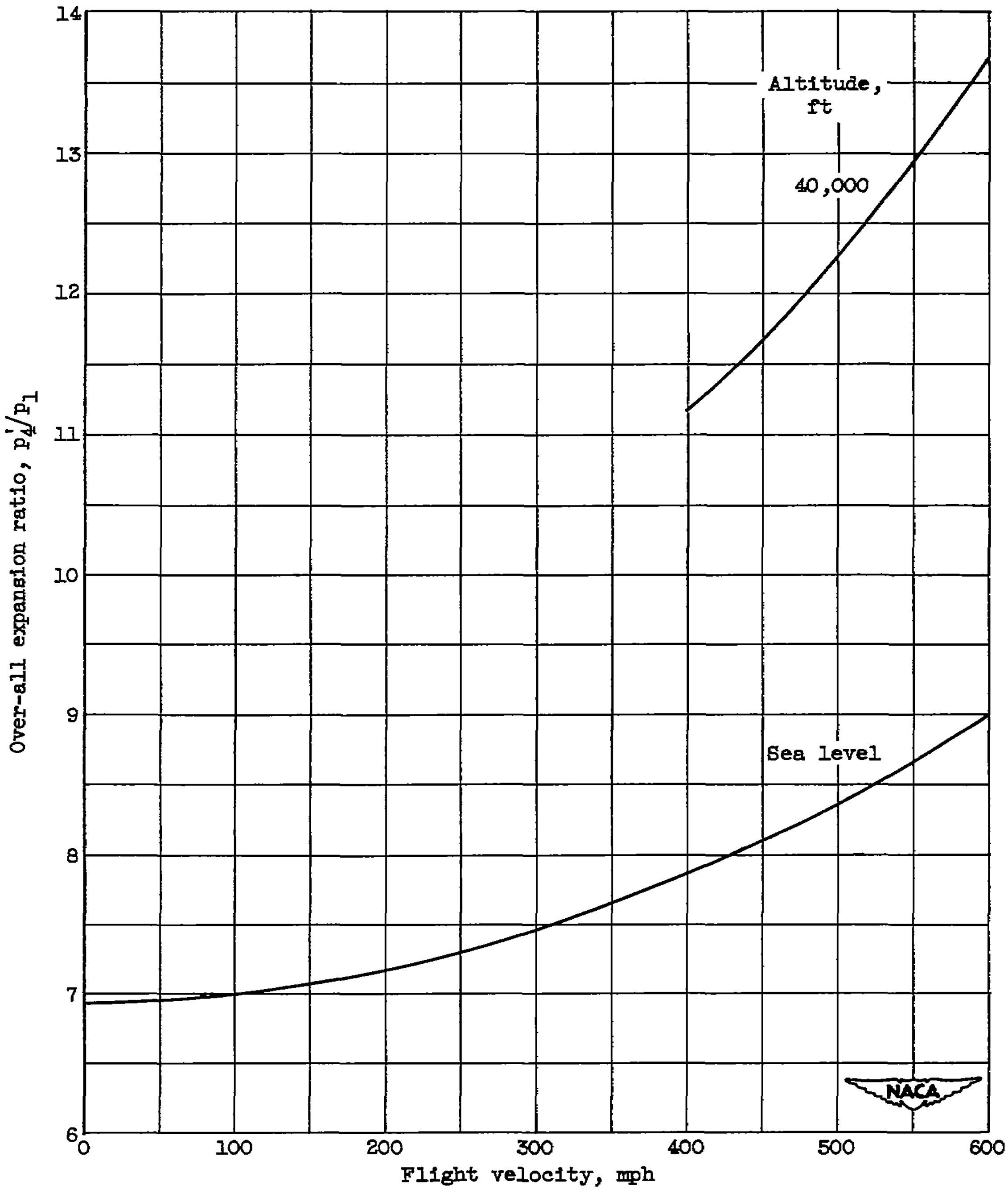
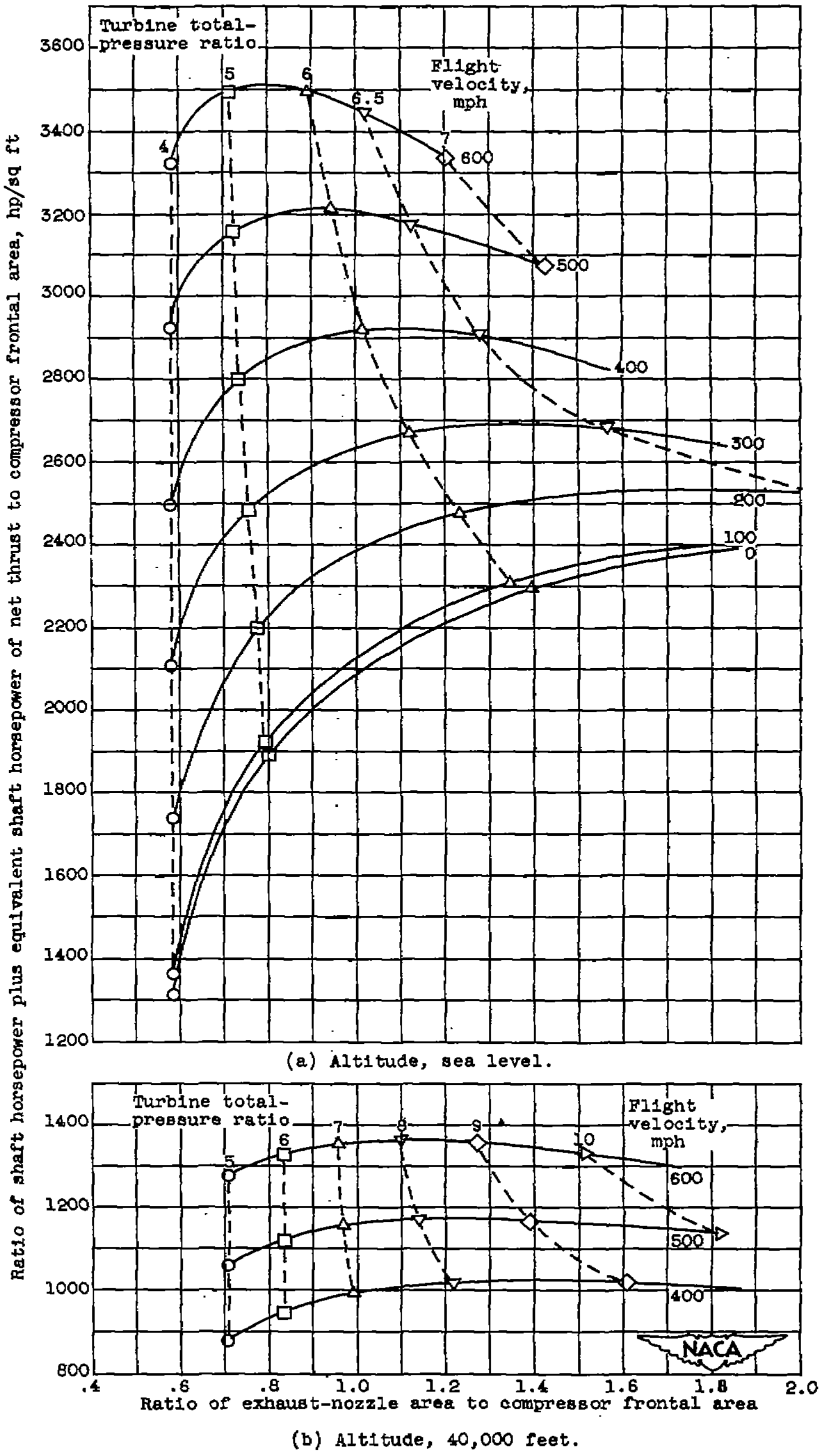


Figure 3. - Effect of altitude and flight velocity on over-all expansion ratio. Turbine-inlet total temperature, 2060° R; design rotative speed.



(b) Altitude, 40,000 feet.

Figure 4. - Effect of flight conditions on turbine design requirements. Turbine-inlet total temperature, 2060° R; design rotative speed.

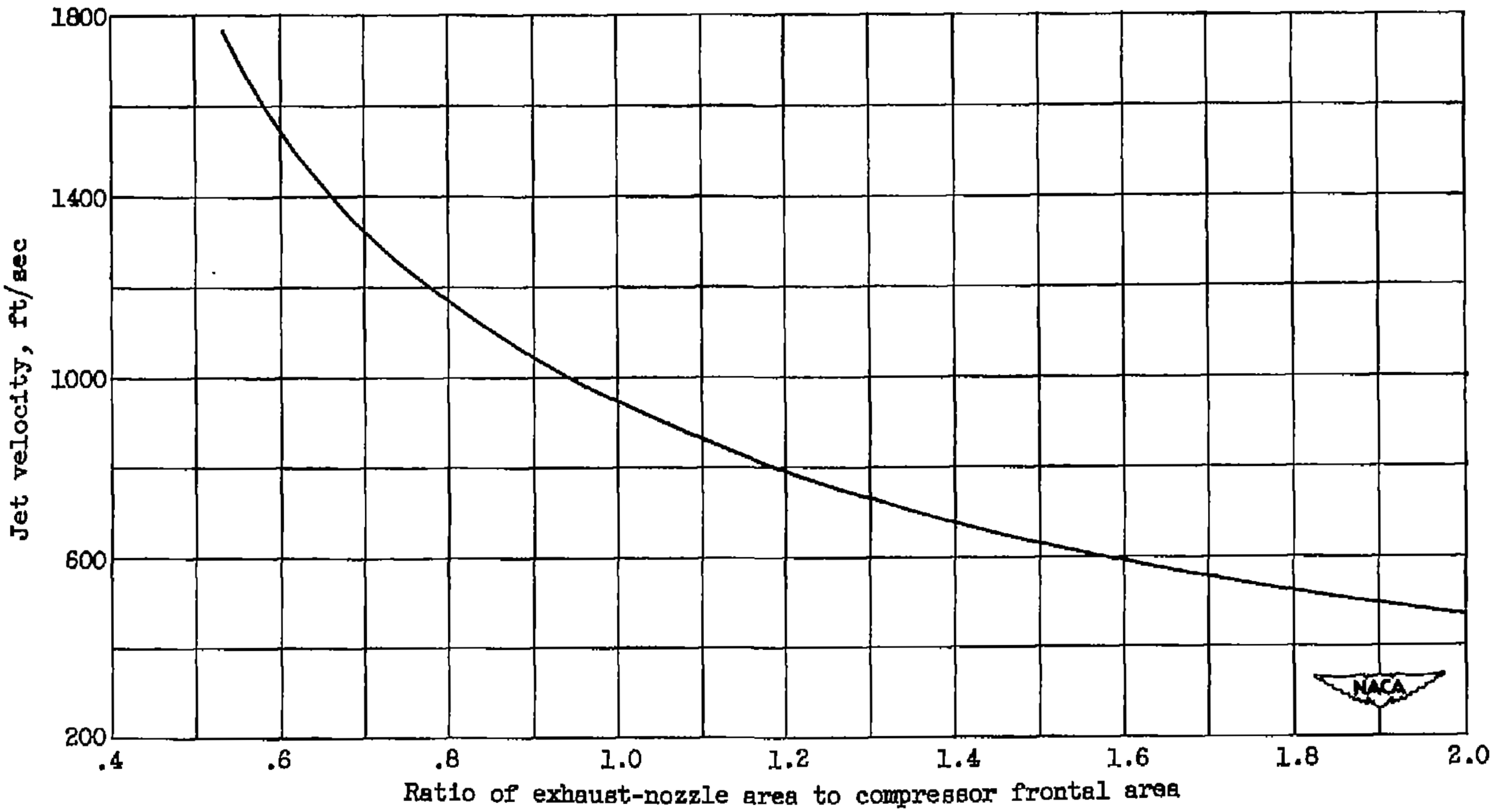
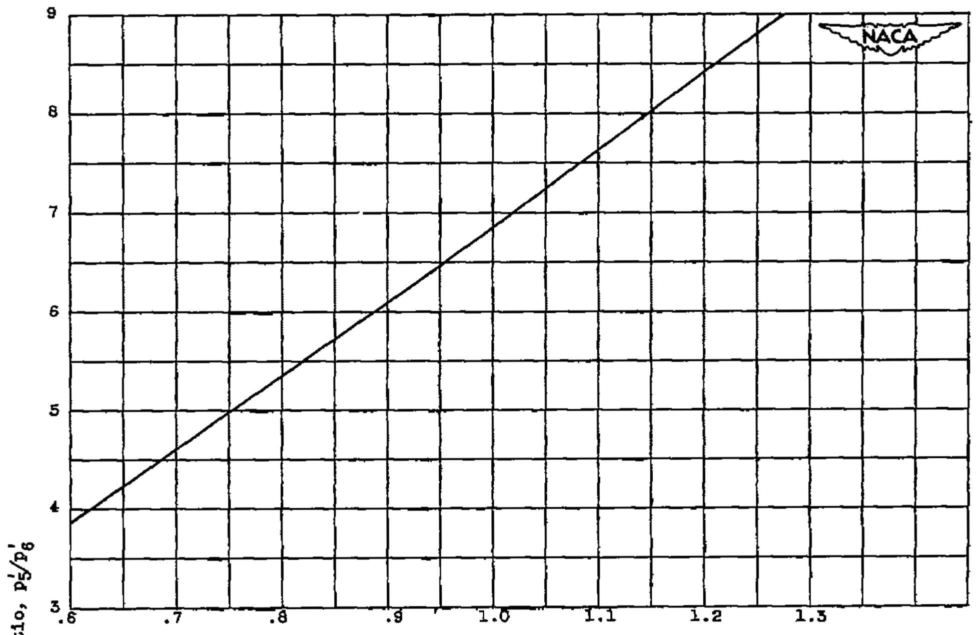
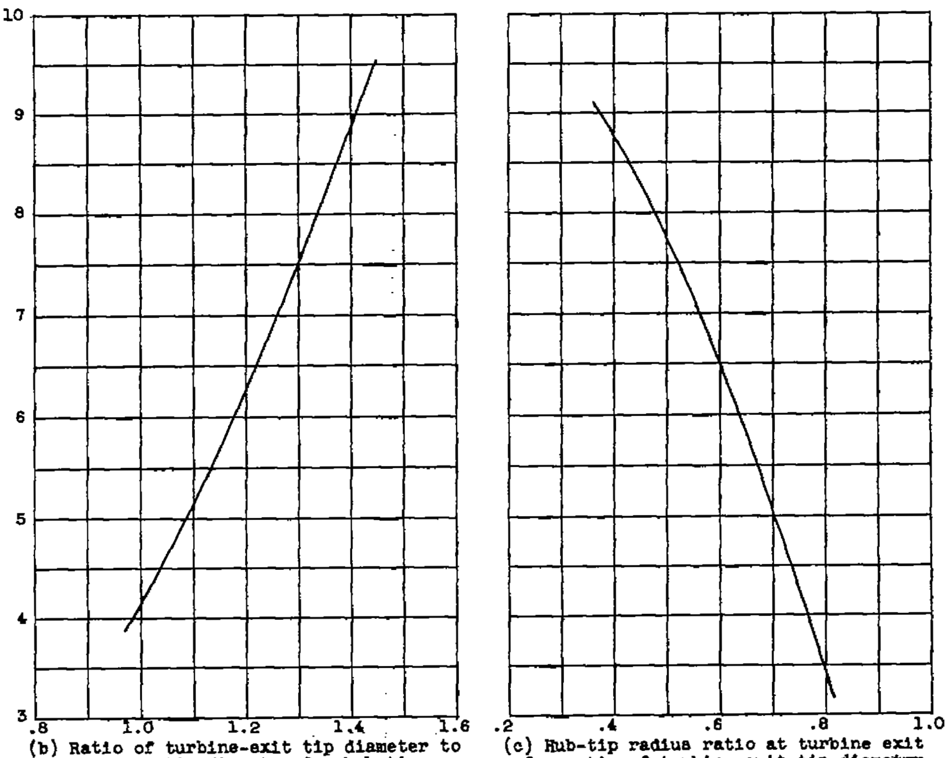


Figure 5. - Effect of exhaust-nozzle area on jet velocity. Sea-level static condition; turbine-inlet total temperature, 2060° R; design rotative speed.



(a) Ratio of turbine-exit annular area to compressor frontal area.



(b) Ratio of turbine-exit tip diameter to compressor tip diameter for hub-tip radius ratio of 0.6 at turbine exit.

(c) Hub-tip radius ratio at turbine exit for ratio of turbine-exit tip diameter to compressor tip diameter of 1.22.

Figure 6. - Useful turbine total-pressure ratio obtainable with given turbine-exit geometry.

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SECURITY INFORMATION

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